Copy No. 10

NASA PROGRAM APOLLO WORKING PAPER NO. 1162

DOUBLE HOHMANN TRANSFER CONCEPT FOR LEM INTERCEPT AND RENDEZVOUS WITH CSM

SEP 1970
RECEIVED
NASA STI FACILITY
INPUT BRANCH

FACILITY FORM 602
N70-76111 (ACCESSION NUMBER)
(THRU)
22 (PAGES)
1 (CODE)
TMX-65218 (NASA CR OR TMX OR AD NUMBER)
(CATEGORY)

DISTRIBUTION AND REFERENCING

This paper is not suitable for general distribution or referencing. It may be referenced only in other working correspondence and documents by participating organizations.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

March 12, 1965

NASA PROGRAM APOLLO WORKING PAPER NO. 1162

DOUBLE HOHMANN TRANSFER CONCEPT

FOR LEM INTERCEPT AND RENDEZVOUS WITH CSM

Prepared by: Floyd V. Bennett

Floyd V. Bennett
AST, Theoretical Mechanics Branch

Authorized for Distribution:

Warren Gillespie, Jr.

for Maxime A. Faget
Assistant Director for Engineering and Development

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

March 12, 1965

LIST OF FIGURES

TABLE OF CONTENTS

DOUBLE HOHMANN TRANSFER CONCEPT
FOR LEM INTERCEPT AND RENDEZVOUS WITH CSM

Floyd V. Bennett

SUMMARY

A concept for performing LEM orbit transfer maneuvers to intercept and rendezvous with the CSM is presented. This concept which is a double Hohmann or bielliptic transfer is shown to simplify these orbital maneuvers, thus enhancing the astronaut monitoring and backup guidance capabilities. Furthermore, the rendezvous is perfomed on the earth side of the moon, making possible the assistance of MSFN tracking. Also, use of this concept is shown to provide for compatibility of transfer maneuvers for nominal launch, descent aborts, any-time surface launch, and CSM rescue of LEM crew.

INTRODUCTION

During the LEM active phase of the Apollo mission, it is required for crew safety that the LEM be able to execute, at any time, an abort maneuver to rendezvous with the CSM. The abort trajectories generally consist of powered flight to a safe pericynthion altitude (nominally 50 000 ft) and coasting flight or orbital transfer to intercept the CSM. The current concept for determining the intercept transfers utilizes the well known solution of Lambert's two-impulse problem with the safe pericynthion restriction. Due to the varied initial conditions imposed by requiring an any-time abort situation, these transfers result in a wide variety of terminal approach conditions for performing rendezvous and docking. This is especially true for aborts off the powered descent in which the terminal or closing rates vary from 100 to nearly 400 fps and approach directions vary as much as 90°. It is the purpose of this report to present a concept of orbital intercept transfer which will alleviate somewhat these varied approach conditions for terminal rendezvous.

SYMBOLS

h_{off}	Altitude of offset point for double Hohmann concept, see figure 5
R	Relative range between LEM and CSM
$\dot{R}$	Relative range rate between LEM and CSM
T	Time of transfer to rendezvous
ΔV_A	Velocity increment required for terminal rendezvous
ΔV_{off}	Velocity increment required at the offset altitude for intercept
ΔV_P	Velocity increment required at pericynthion (over circular) to initiate transfer
ΔV_T	Total velocity increment for intercept and rendezvous
θ	Central angle of LEM transfer trajectory for rendezvous
ϕ	Phase angle between LEM and CSM at initiation of transfer

CURRENT LEM MISSION

In the current nominal LEM mission, both the orbital descent and ascent transfers are Hohmann transfers between the 80 n. mi. circular, CSM orbit, and 50 000-foot altitudes (fig. 1). The 50 000-foot altitude is considered a safe pericynthion restriction; hence, continuous powered flight is required below this altitude. Nominally, any out-of-plane requirements are satisfied during the powered launch to the safe pericynthion. Aborts any time during the LEM mission produce a variety of two-impulse intercept transfers in order to provide LEM rendezvous with the CSM (fig. 2). Several studies have been conducted which show the wide variations in the parameters for these transfers, namely, velocity required (both magnitude and direction), time of transfer, and transfer angle. For example, see references 1 through 4. The transfers for aborts during powered descent are shown in these references to produce the widest variations due to the large change in initial phase angle between the two spacecraft during this maneuver (fig. 3). The various phases of the powered descent denoted in figure 3 are consistent with terminology presented in reference 5.

Typical variations of the transfer parameters with spacecraft phase angle are shown in figure 4. The large change shown in the terminal rendezvous velocity ΔV_A complicates this maneuver considerably. For example, closing velocities above 200 fps must be nulled by the main engine, whereas below this level the RCS jets are used. The direction of these closing velocities, although not shown, varies between 0° and 90° which produces a nonstandard background (star, sun, or surface). The variations in transfer angle and time cause the rendezvous to be performed at a wide range of locations in the CSM orbit. This increases the difficulties of star pattern background recognition which could be a valuable aid for crew monitoring or for manual backup guidance techniques. Also, when the lunar surface is in the background, it is sometimes lit and sometimes dark, depending on the transfer angle.

In summary, the wide range of transfer parameters leads to a wide range of terminal rendezvous conditions consequently complicating guidance techniques (primary, backup, and monitoring) as well as crew training. A concept of intercept transfer designed to somewhat alleviate the variations at terminal rendezvous is presented in the following section.

DOUBLE HOHMANN TRANSFER

Basic Concept

The double Hohmann or bielliptic transfer consists of a Hohmann transfer to an altitude offset from the CSM immediately followed by another Hohmann transfer to rendezvous as shown in figure 5. For this concept, notice that the point of rendezvous always occurs 360° from the launch burnout point. Since the launch burnout point occurs within a 22° band for aborts off the powered descent (fig. 3), then the rendezvous will also occur in this band. Furthermore, the rendezvous is now on the earth side of the moon and can therefore be assisted by ground tracking (MSFN). Also, since the transfers are Hohmann type, all velocity increments (at launch burnout, offset, and rendezvous) are always added tangentially. The equations for determining the parameters for this concept are presented in the appendix.

Variation of Parameters

The incremental velocity requirements for this concept are shown in figure 6 for the range-of-phase angle encountered for aborts off the powered descent (fig. 3). These results show that the total velocity is as much as 200 fps less than the current technique for early aborts.

The arrival of closing velocity ΔV_A is always less than 100 fps, thus simplifying terminal rendezvous engine and guidance logic. The velocity input at the offset point ΔV_{off} is nearly a constant (between 95 and 99 fps) which simplifies lunar backside (away from earth) maneuvers. The variation of offset altitude and total time to rendezvous with spacecraft phase angle is shown in figure 7. The offset altitude varies linearlly between 50 000 feet and 150 n. mi. for the phase angle range of interest. The time is nearly constant varying only between 113 and 126 minutes. This is roughly an hour longer than the current nominal and approximately 30 minutes longer than the early abort at initiation of powered descent (fig. 4). However, the additional time required is not considered unreasonable nor a serious drawback to the concept. Furthermore, this increase in time need not increase total (Apollo) mission time, as injection into the trans-earth (earth return) trajectory can be initiated on the same lunar orbit pass as in the current concept. However, significant increases in nominal rendezvous time beyond this (approximately 2 hours) could cause increases in both CSM lifetime and LEM contingency lifetime requirements.

Singularity

The singularity noted in figure 7 for an offset altitude of 80 n. mi. corresponds to no offset (note that $\Delta V_A = 0$, see fig. 6); that is, rendezvous would actually take place at the end of the first Hohmann (about 58 min) which is the current nominal concept. This would represent a deviation from the double Hohmann concept, but should not present any difficulties, however, if it were desired, Hohmann transfers near this altitude could be deleted, for example, between 75 and 85 n. mi. That is, if launch burnout occurred between phase angles of $-10.7°$ and $-8.1°$ (fig. 7), then execution of the first Hohmann could be delayed a maximum of 8 minutes in order to avoid the singularity region, or surface launch could be delayed a maximum of 1 minute and no orbital delay would be required.

Nominal Transfer

In the current LEM mission profile, the nominal transfer after launch burnout is the Hohmann to 80 n. mi. In the double Hohmann concept, this transfer was shown in the preceding section to represent a singularity point; however, if desired, it could still be used. It is recommended, however, that an offset altitude below 80 n. mi. be used nominally in order to take full advantage of the double Hohmann concept; that is, earth side rendezvous and low terminal rates. For example, for offset altitudes between 50 and 70 n. mi., the arrival velocity would vary only between 40 and 13 fps (fig. 6). Also, the phase angle for these transfers -17.3° to -12.0° occur for aborts during the final approach and touchdown phase of powered descent (fig. 3). Hence, this worse case abort situation could be made to coincide with nominal launch conditions. Also, it was shown in figure 6 that the total velocity requirements are constant for all double Hohmann transfers with offset altitudes less than or equal to 80 n. mi. This is because the energy of these transfer orbits never exceeds that of the CSM.

Launch Window

In the current two-impulse transfer concept, the launch window is obtained by launching later than the time for nominal Hohmann transfer to 80 n. mi. and coasting in the minimum safe altitude (50 000 ft) circular orbit until the proper phasing is obtained. This also changes the point in lunar orbit at which terminal rendezvous occurs, thus presenting varied lighting conditions and star patterns. In the double Hohmann transfer, the launch window is obtained by launching later than the time for nominal launch and merely adjusting the offset altitude for initiation of the second Hohmann transfer. If the nominal launch was chosen as the 70 n. mi. (-12.0° phase angle) offset transfer, then the launch could be delayed approximately 5 minutes (-28.1° phase angle) before coasting at the minimum safe altitude, and change of rendezvous point would be required. For both concepts, the launch windows are defined as not requiring increases in ΔV over the nominal.

Compatibility with Astronaut Capabilities

In the current two-impulse abort transfer trajectories, the velocity increments (magnitude and direction) for intercept and rendezvous are determined by solving, with the aid of a computer, Lambert's problem. For the double Hohmann transfer concept, the astronaut can readily determine the velocity inputs (both magnitude and direction) from the linear relationship with spacecraft phase angle shown in figure 6. (This phase angle is directly related to the elevation of the CSM above the local horizon which the astronaut can measure.) The direction of the velocity inputs is always along the local horizon. Also, since the approach to terminal rendezvous is always a Hohmann type transfer, the range-range rate profile will be similar for all aborts. Indeed, in figure 8 this profile is shown to vary primarily by only a scale factor. (In this figure, the profiles are normalized about the earliest abort-off powered descent, 150 n. mi. offset.) Thus, the simplifications in the velocity inputs offered by this concept should increase the ability of the astronaut to perform backup guidance and/or monitoring of primary guidance.

Any-Time Launch

In the event that the LEM must launch at some time when the phase angle is other than that shown in figure 3, the double Hohmann technique is still applicable. It would be required, however, for phasing that a coast period be added either before or between the two Hohmann transfers. Also, a Hohmann transfer by the CSM for speed-up of phasing (due to limited time of LEM life support system) may be required (ref. 3). Hence, the transfer maneuvers for any time launch situation are compatible with the double Hohmann concept of nominal LEM transfer.

CSM Rescue of LEM

In the event the LEM becomes inactive after reaching a safe pericynthion orbit, the CSM has the ΔV capability to transfer to pickup or rescue the LEM crew. Several analyses of this problem have been reported (refs. 6 and 7). In these studies it is shown that the CSM transfers on a Hohmann trajectory to a circular phasing (comparable to offset in present concept), coasts, and then transfers on another Hohmann trajectory to intercept and rendezvous with the LEM (reverse of LEM active procedure for any time launch). Hence, the double Hohmann transfer maneuvers are also compatible with the CSM rescue maneuvers. Consequently, the same guidance techniques and astronaut training procedures can be used for nominal launch, descent aborts, any-time launch, and CSM rescue operations.

CONCLUDING REMARKS

A concept for performing LEM orbit transfer maneuvers to intercept and rendezvous with the CSM has been presented. This concept which is a double Hohmann or bielliptic transfer is shown to have advantages over the current design concept of two-impulse transfers. These advantages include (1) reduction in total ΔV for descent aborts, (2) reduction in ΔV for terminal rendezvous, (3) earth side rendezvous makes possible MSFN assistance, (4) velocity inputs are always directed along the local horizon, (5) for descent aborts and nominal launch the time and location of rendezvous are nearly constant, (6) guidance techniques and astronaut training procedures are compatible for nominal launch, descent aborts, any time launch, and CSM rescue transfers, (7) surface launch window is increased without minimum altitude coasting, changes in ΔV, or changes in rendezvous point, and (8) astronaut monitoring and backup guidance capabilities are enhanced through simplifications afforded by this concept. It is proposed that the double Hohmann transfer concept be reviewed by appropriate MSC organizational elements for possible utilization for design and operation of the LEM mission.

REFERENCES

1. Ernull, Robert E.; and Sanders, Roger H.: Optimized Abort Rendezvous from Hohmann Transfer. MSC Internal Note No. 64-FM-28, Aug. 21, 1964.

2. Frank, M. P.: LEM Abort from Main Powered Descent. MSC Internal Note No. 64-FM-31, Aug. 21, 1964.

3. Gray, Amelia J.; and Stull, Paul J.: Study of LEM Abort Transfer Trajectories. MSC Internal Note No. 64-EG-20, Aug. 26, 1964.

4. Yenchoris, Jerome D.: Comparison of Two Abort Maneuvers from Main Powered Descent. MSC Internal Note No. 64-FM-46, Oct. 14, 1964.

5. Cheatham, Donald C.: A Proposed Terminology from the LEM Powered Descent and Landing Maneuver. MSC Internal Note No. 64-EG-27, Nov. 23, 1964.

6. Price, Charles R.; and Bennett, Floyd V.: A Brief Investigation of CSM Rescue of LEM. MSC Internal Note No. 64-EG-2, Feb. 25, 1964.

7. Price, Charles R.: Extension of Investigation of CSM Rescue of LEM. MSC Internal Note No. 64-EG-19, Sept. 10, 1964.

APPENDIX

EQUATIONS FOR DOUBLE HOHMANN TRANSFER CONCEPT

The equations for determining the parameters for the double Hohmann transfer concept are presented herein. These equations are based on a central gravitational body and impulsive thrusting.

Velocity Increments

The expressions for the velocity increments are:

a. Overspeed at launch burnout, ΔV_P

$$\Delta V_P = V_{BO}\left(\sqrt{\frac{R_{off}}{A_1}} - 1\right) \tag{1}$$

b. Velocity increment at offset altitude, ΔV_{off}

$$\Delta V_{off} = V_{off}\left(\sqrt{\frac{R_{off}}{A_2}} - \sqrt{\frac{R_{off}}{A_1}}\right) \tag{2}$$

c. Velocity increment at terminal rendezvous, ΔV_A

$$\Delta V_A = V_{csm}\left(1 - \sqrt{\frac{R_{csm}}{A_2}}\right) \tag{3}$$

where

R_{off}	radius from center of moon to offset altitude
R_{csm}	radius from center of moon to CSM altitude
A_1	semi-major axis of first Hohmann transfer (from launch burnout to offset altitude)
A_2	semi-major axis of second Hohmann transfer (from offset to CSM altitude)

V_{BO} circular orbital velocity at launch burnout altitude

V_{off} circular orbital velocity at offset altitude

V_{csm} circular orbital velocity of CSM

Spacecraft Phase Angle

The phase angle between the spacecrafts is determined from the following relationships:

a. Phase angle at initiation of first Hohmann transfer (transfer from burnout to offset altitude), ϕ_1, radians

$$\phi_1 = \pi \left[\left(\frac{A_2}{R_{csm}} \right)^{3/2} + \left(\frac{A_1}{R_{csm}} \right)^{3/2} - 2 \right] \tag{4}$$

b. Phase angle at initiation of second Hohmann transfer (transfer from offset to CSM), ϕ_2, radians

$$\phi_2 = \pi \left[\left(\frac{A_2}{R_{csm}} \right)^{3/2} - 1 \right] \tag{5}$$

Phase angle is positive for LEM leading CSM.

Offset Radius

For the double Hohmann transfer concept given the spacecraft phase angle at launch burnout ϕ_1, it is necessary to determine the offset radius for the first Hohmann transfer. It can be seen from equation (4) that R_{off} is a complex function of ϕ_1 since

$$A_1 = \frac{1}{2}\left(R_{BO} + R_{off}\right) \tag{6}$$

$$A_2 = \frac{1}{2}\left(R_{csm} + R_{off}\right) \tag{7}$$

and where R_{BO} is launch burnout radius from center moon. Thus, it is necessary to solve equation (4) for R_{off} by an iteration procedure. It was shown in figure 7 that the offset altitude is nearly linear with ϕ_1 for the parameter range of interest; therefore, the iteration should be straight forward. Or, equation (4) can be solved directly for ϕ_1 given R_{off} (as was done in the present study) and then interpolate for the desired offset radius. The accuracy of the offset radius is not of a critical nature as midcourse corrections can be performed on either or both Hohmann transfers; hence, linear interpolation should suffice.

Transfer Time

The expressions for calculating the time of each Hohmann transfer are:

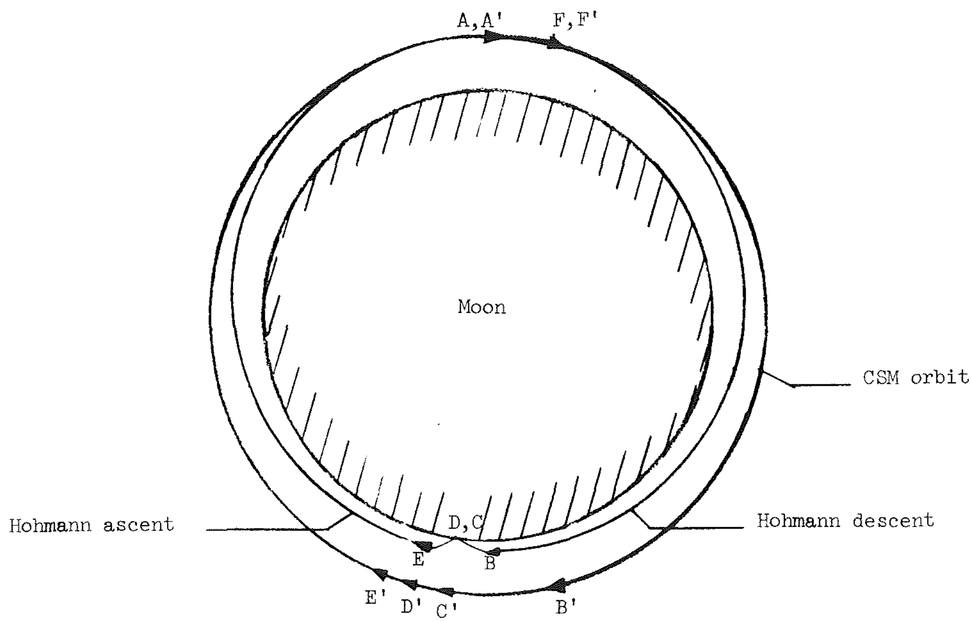
a. Time of first Hohmann transfer, T_1

$$T_1 = \pi\sqrt{\frac{A_1^3}{\mu}} \tag{8}$$

b. Time of second Hohmann transfer, T_2

$$T_2 = \pi\sqrt{\frac{A_2^3}{\mu}} \tag{9}$$

where μ is gravitational constant of central body. The total time to rendezvous is then the sum of T_1 and T_2.



A LEM separation and insertion into Hohmann descent

B Initiation of powered descent

C Hover, translation and touchdown

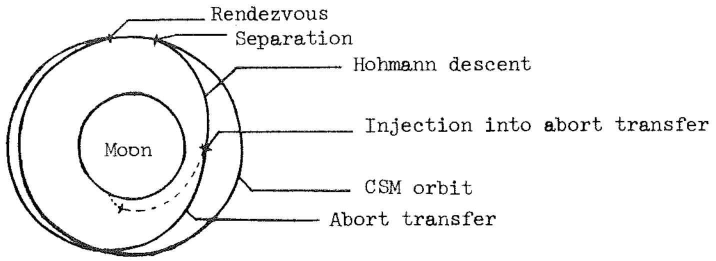
D Launch

E Insertion into Hohmann ascent

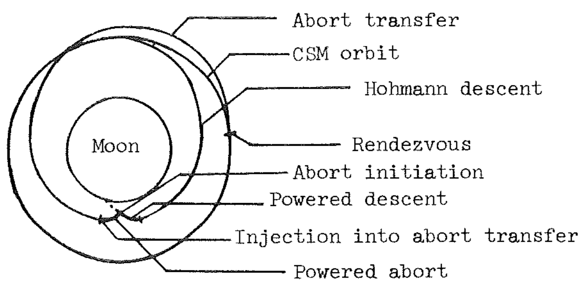
F Terminal rendezvous and docking

(primes denote corresponding position of CSM)

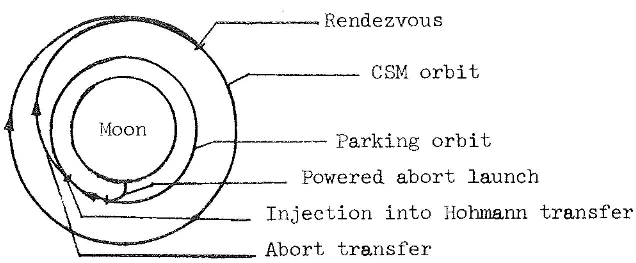
Figure 1.- Nominal LEM mission.



a) Abort from Hohmann descent



b) Abort from powered descent



c) Abort from surface

Figure 2.- Abort phases.

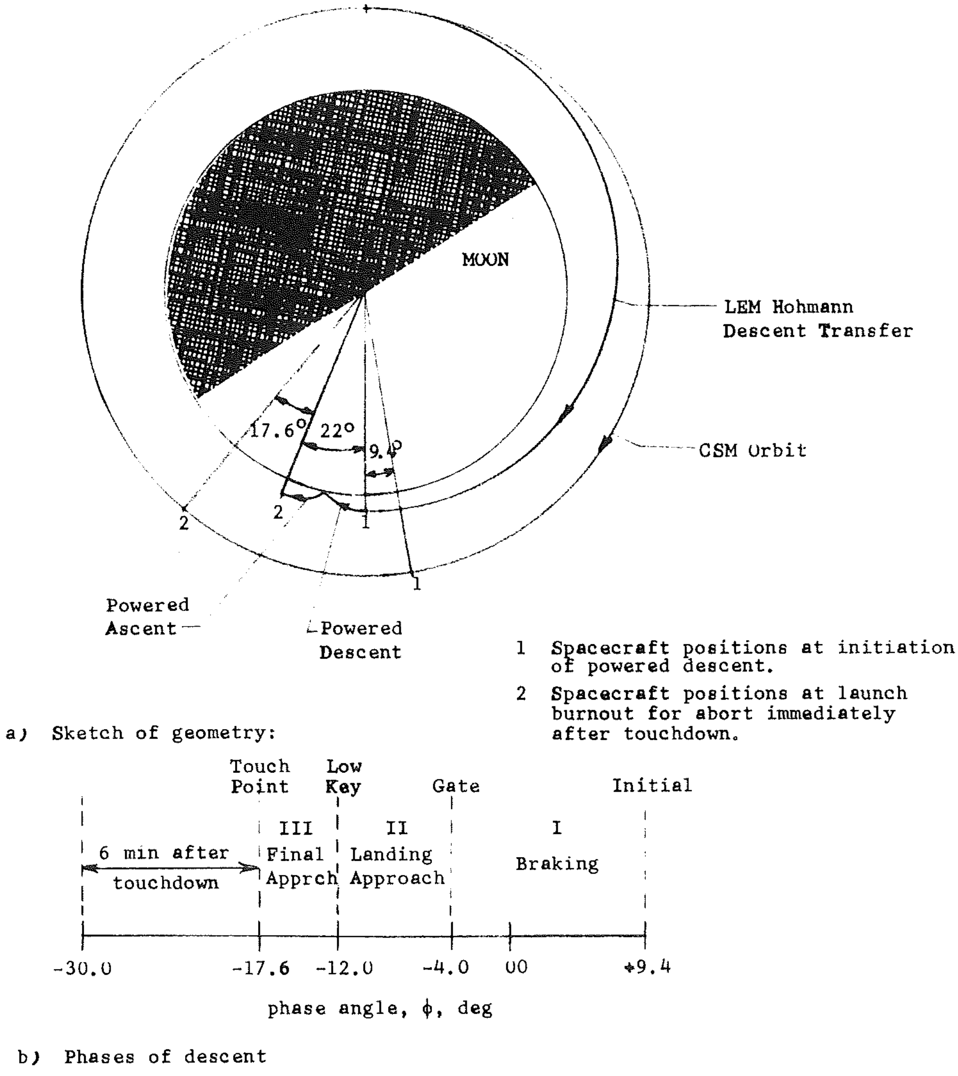


Figure 3.- Range of spacecraft phase angle for aborts anytime during nominal powered descent (LEM at 50 000 ft).

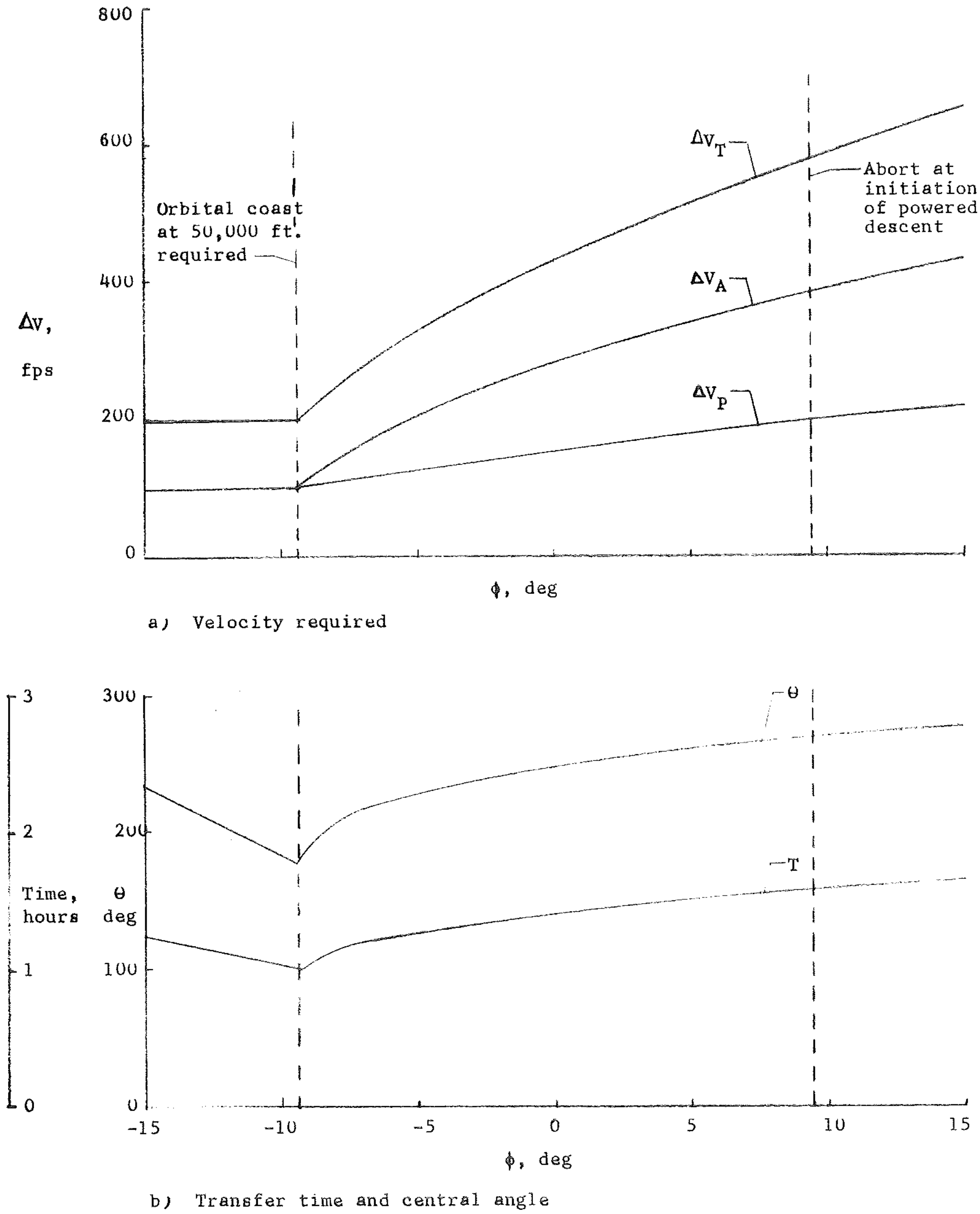


Figure 4.- Variation of transfer parameters for aborts off powered descent (pericynthion restricted to 50 000 ft).

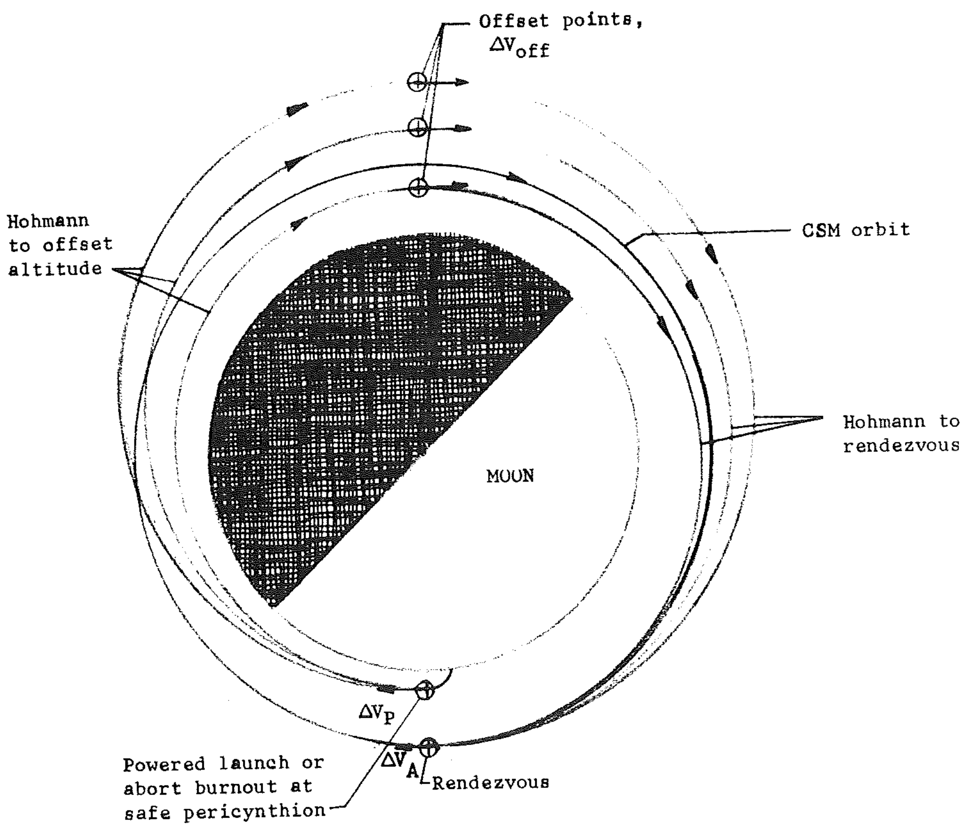


Figure 5.- Sketch of double Hohmann intercept transfer concept.

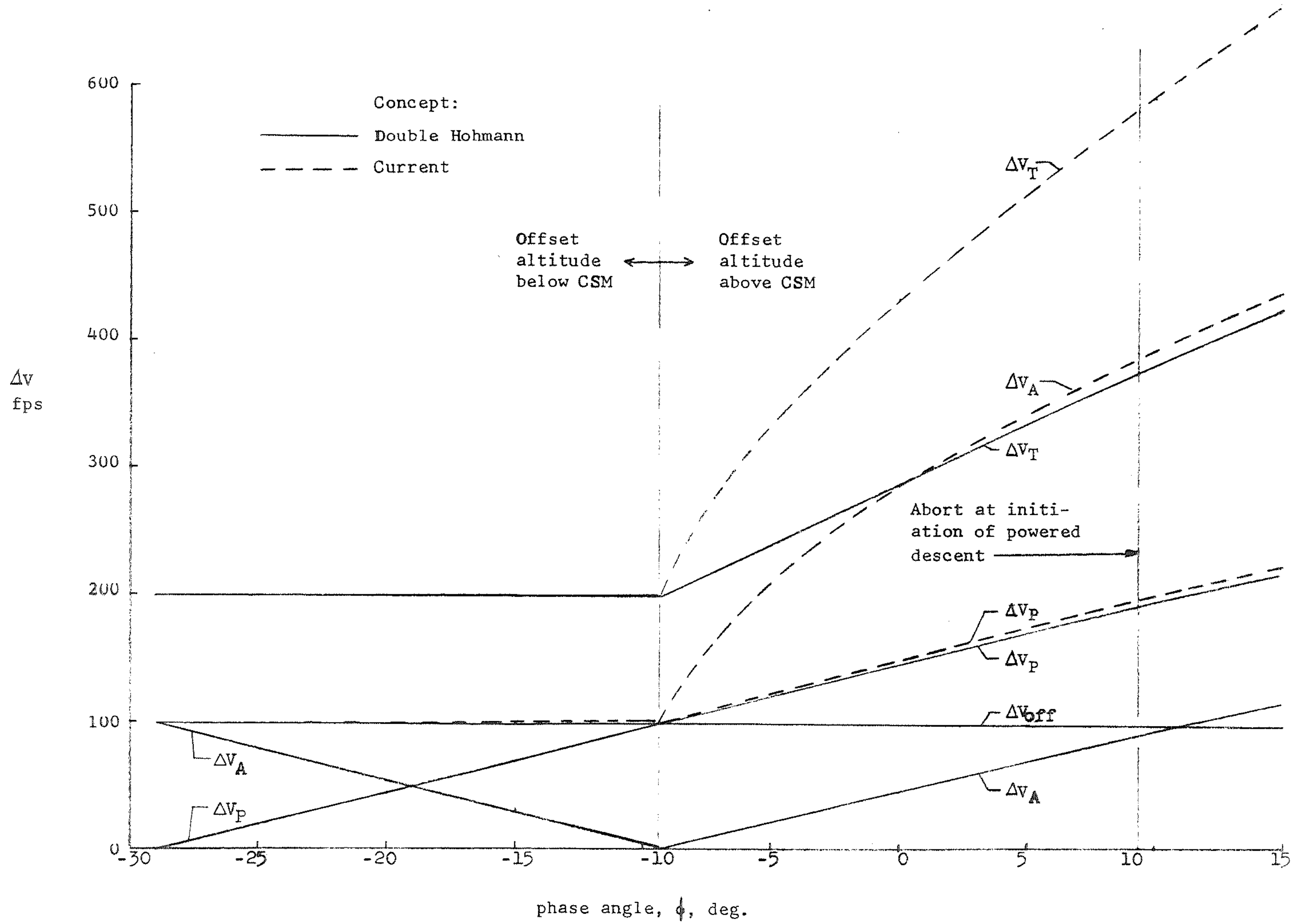


Figure 6.- Velocity requirements for double Hohmann concept for transfer from 50 000 ft circular orbit to CSM at 80 n. mi. circular orbit.

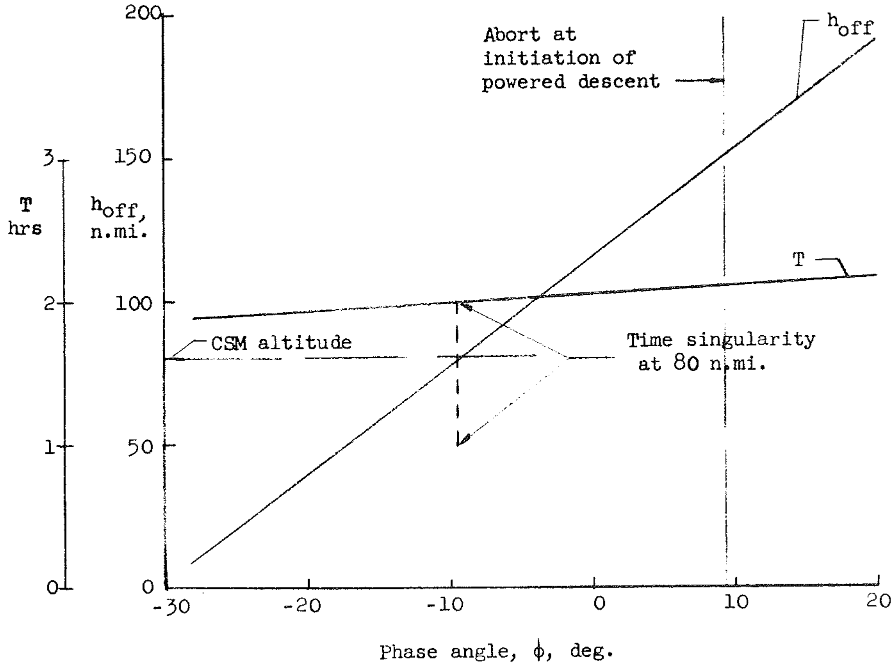
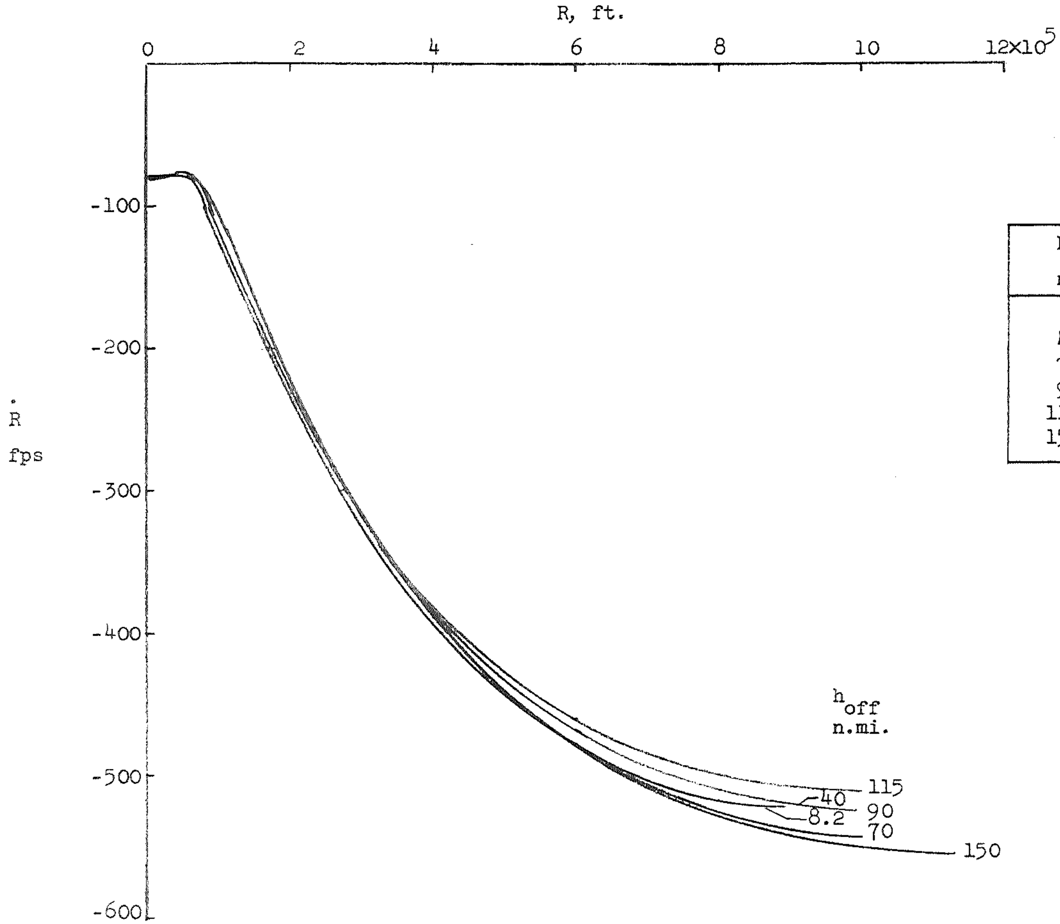


Figure 7.- Variation of offset altitude and total time to rendezvous with spacecraft phase angle.



h_{off} n.mi.	Scale Factor
8.2	0.83
40	1.52
70	0.65
90	6.32
115	1.80
150	1.00

Figure 8.- Range-Range rate profiles for double Hohmann concept.